HPC for First-principles Simulations of Astrophysical Plasmas

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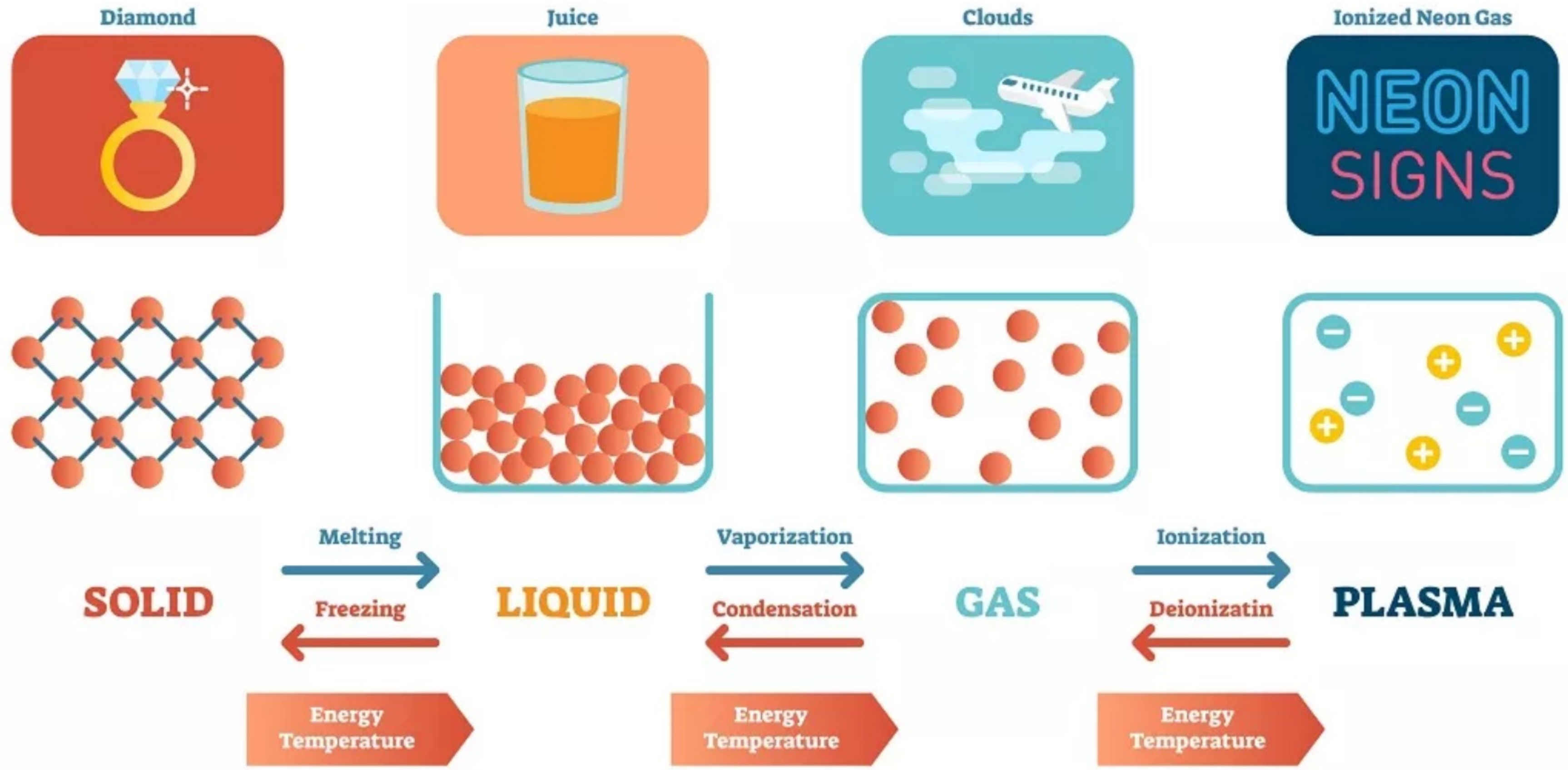
Hello World!

- Fabio Bacchini, PhD
- PhD in 2018, postdocs in Germany, Belgium, USA
- Since 2022: Assistant Professor at the Centre for mathematical Plasma Astrophysics, KU Leuven
- Research group: 9 PhD students, 7 postdocs
- Research focus:
  - Heliospheric plasma physics
  - High-energy astroplasma physics
  - High-performance computing
  - Numerical methods

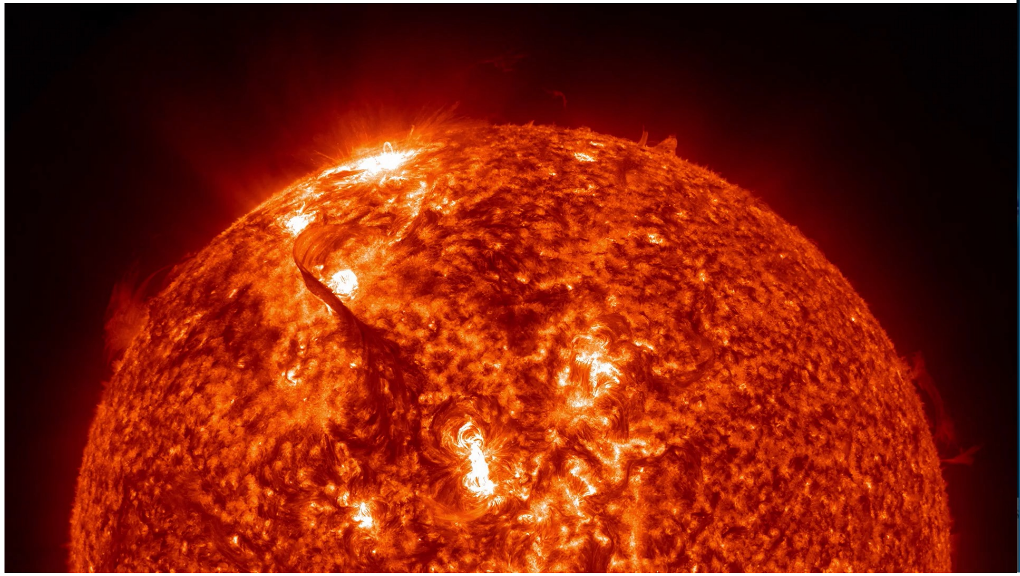
What is a Plasma?

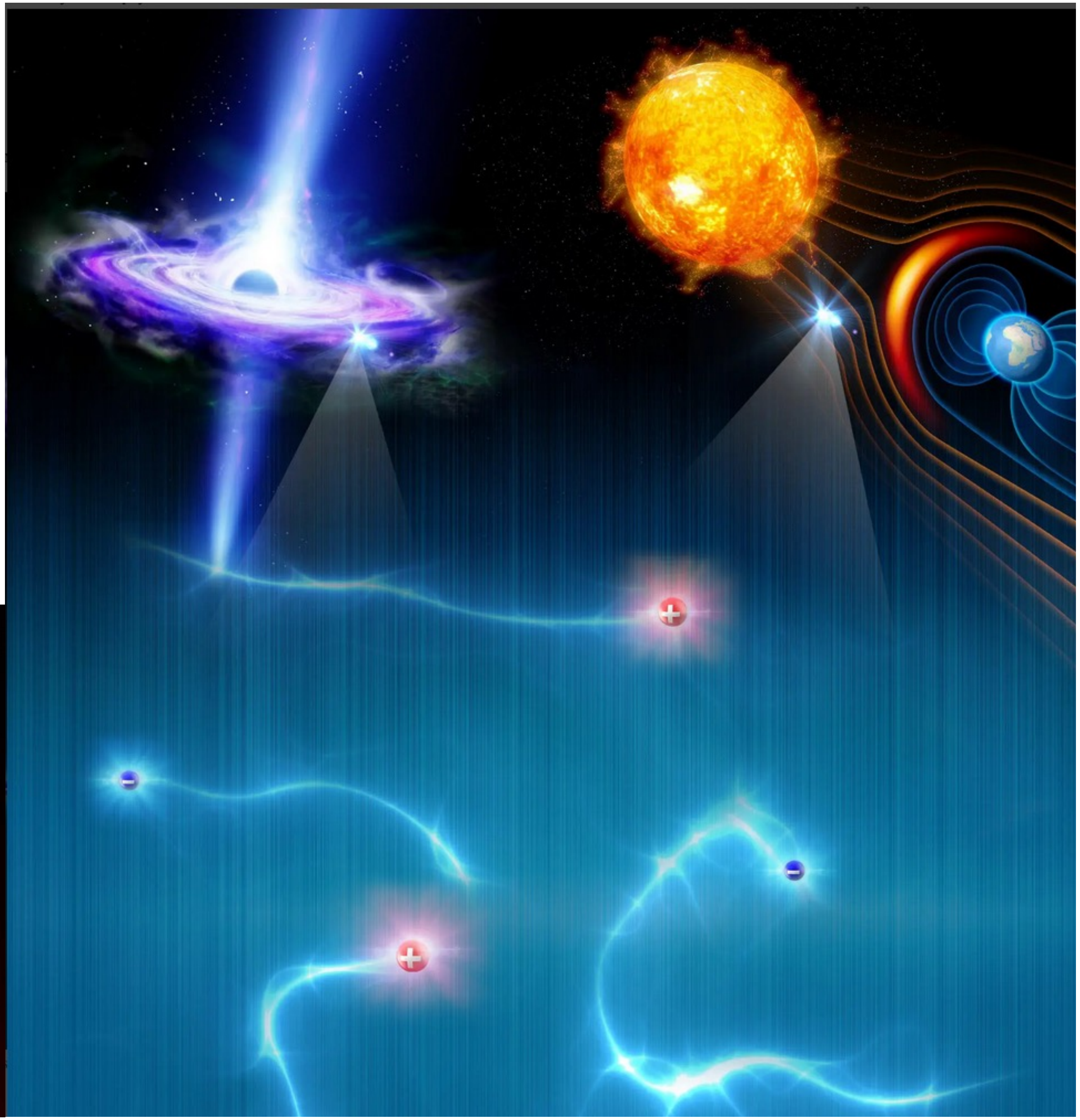
- A state of matter where individual charged particles are free to move
- Found on Earth and in space
- The Universe is 99% plasma!!!



Plasmas in Space

- The Sun is made of plasma
- The Earth is surrounded by plasma
- Each and every galaxy is made of plasma
- Black holes are surrounded by plasma





What Makes Plasma so Interesting?

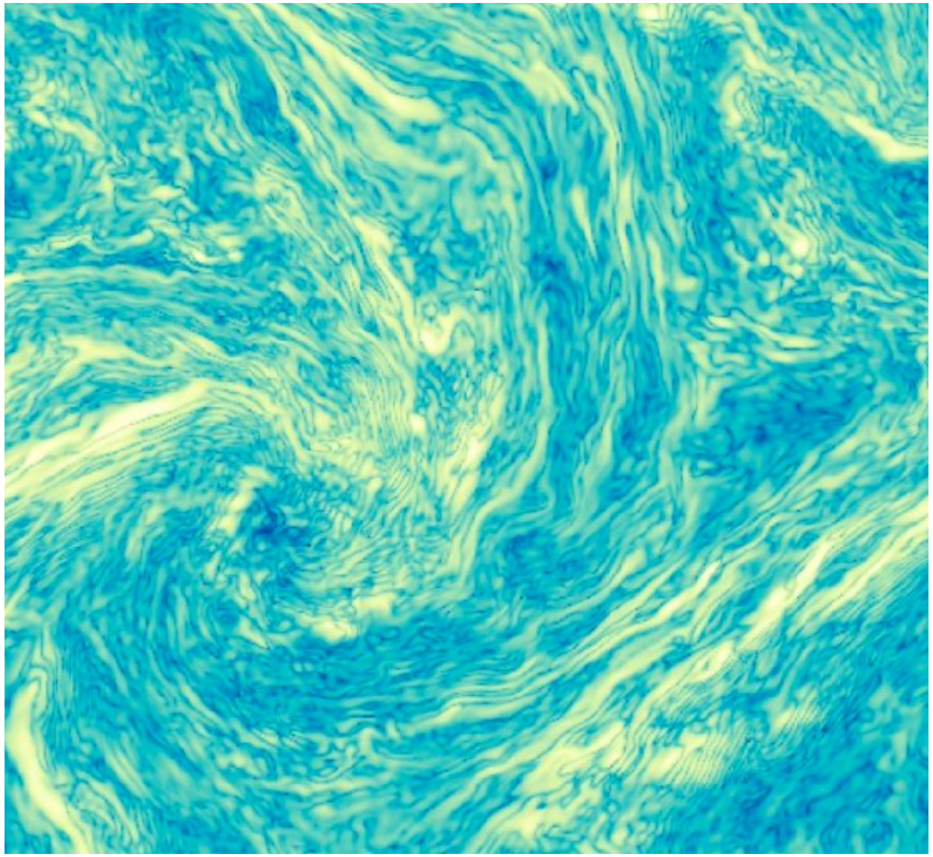
- Most common state of matter in the Universe

- Important practical applications
  - Fusion
  - Propulsion
  - Torches
  - …

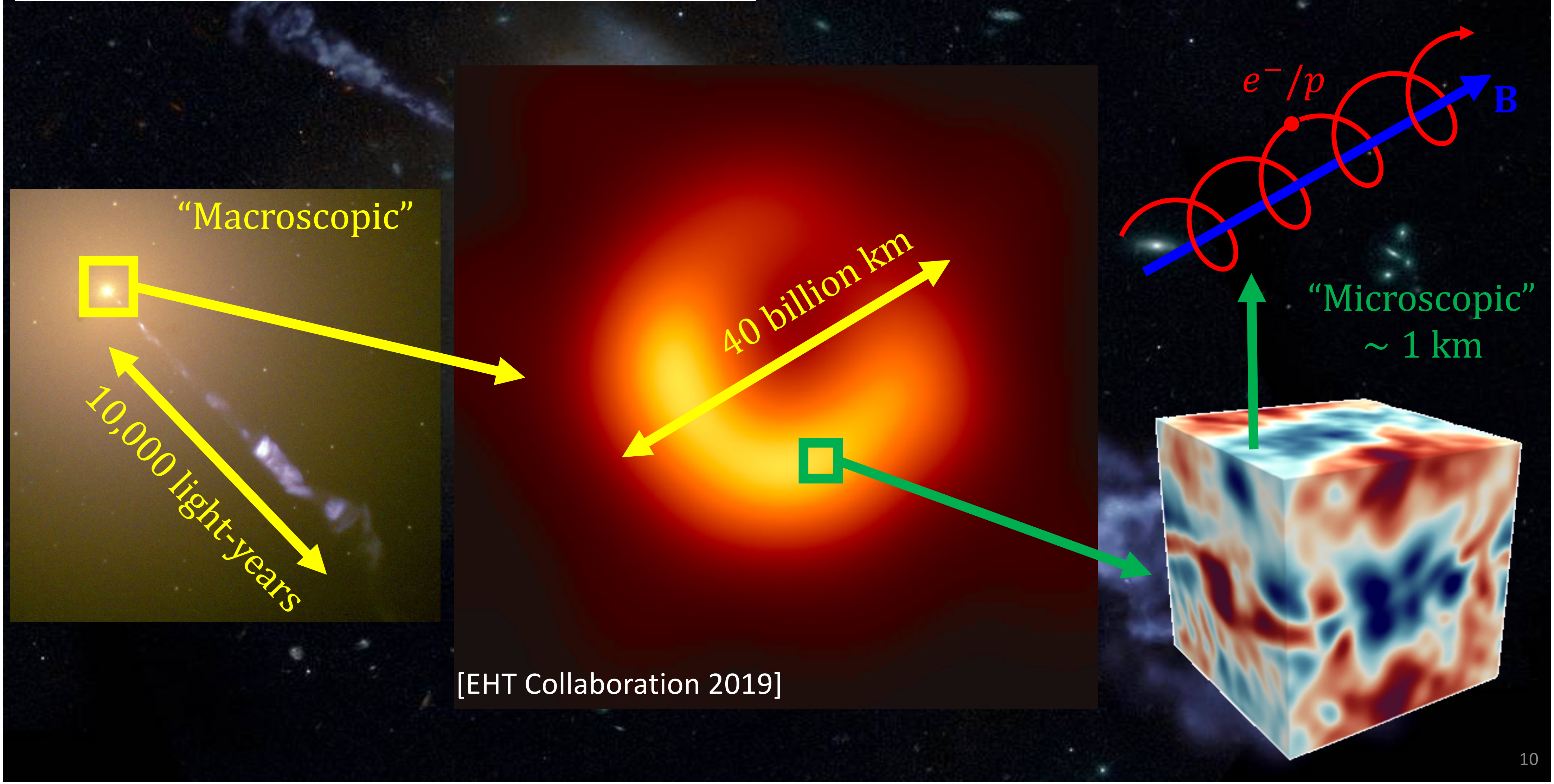
- Earth is at risk due to solar activity!

- By studying plasmas, we can study unreachable space environments (e.g. black-hole surroundings)

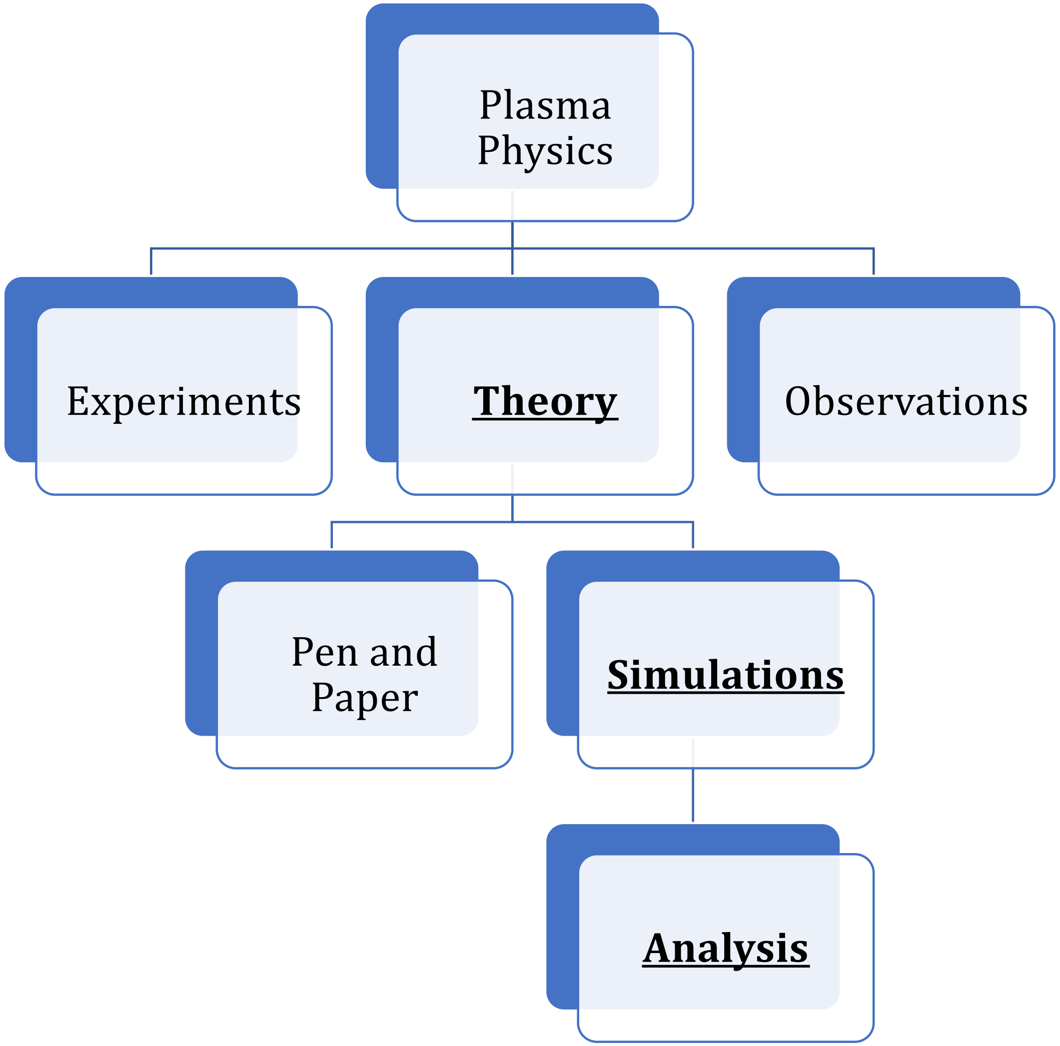
Most importantly: Beautiful visuals!



"Multiscale, Multiphysics"



How Do We Study Plasmas?



Supercomputing for Astroplasmas

- (Astro)plasma research requires supercomputing facilities
- Typical simulations run on (hundreds of) thousands of CPUs to speed up calculations
- New (for scientists): Exploit GPUs and exascale
- Constant need for efficient visualization workflows!

[Hortense@VSC]

[LUMI@CSC]

A Journey Through Physics and Scales

- Plasma simulations have addressed a great variety of astrophysical phenomena and scenario

- Approaches vary significantly depending on length/time scales, regimes, and energies involved

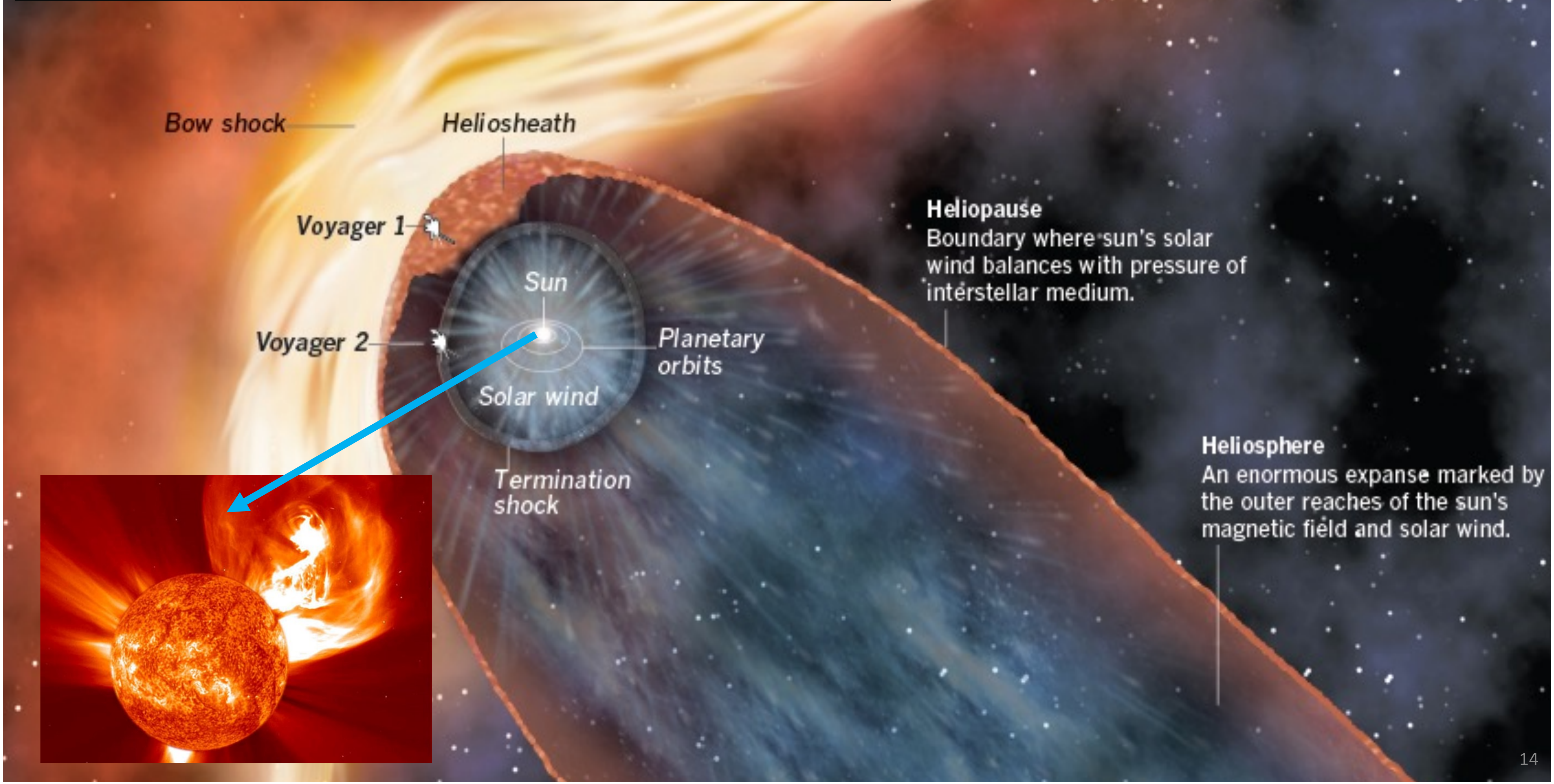
- Extra physics may need inclusion:
  - Collisional effects
  - Multiple particle species
  - Radiation effects
  - QED effects
  - Forcing effects (expansion/compression, shearing, …)
  - …

SCALE: MICRO — MESO — MACRO

ENERGY: NEWTONIAN — TRANSRELATIVISTIC — RELATIVISTIC

REGIME: KINETIC — HYBRID — FLUID

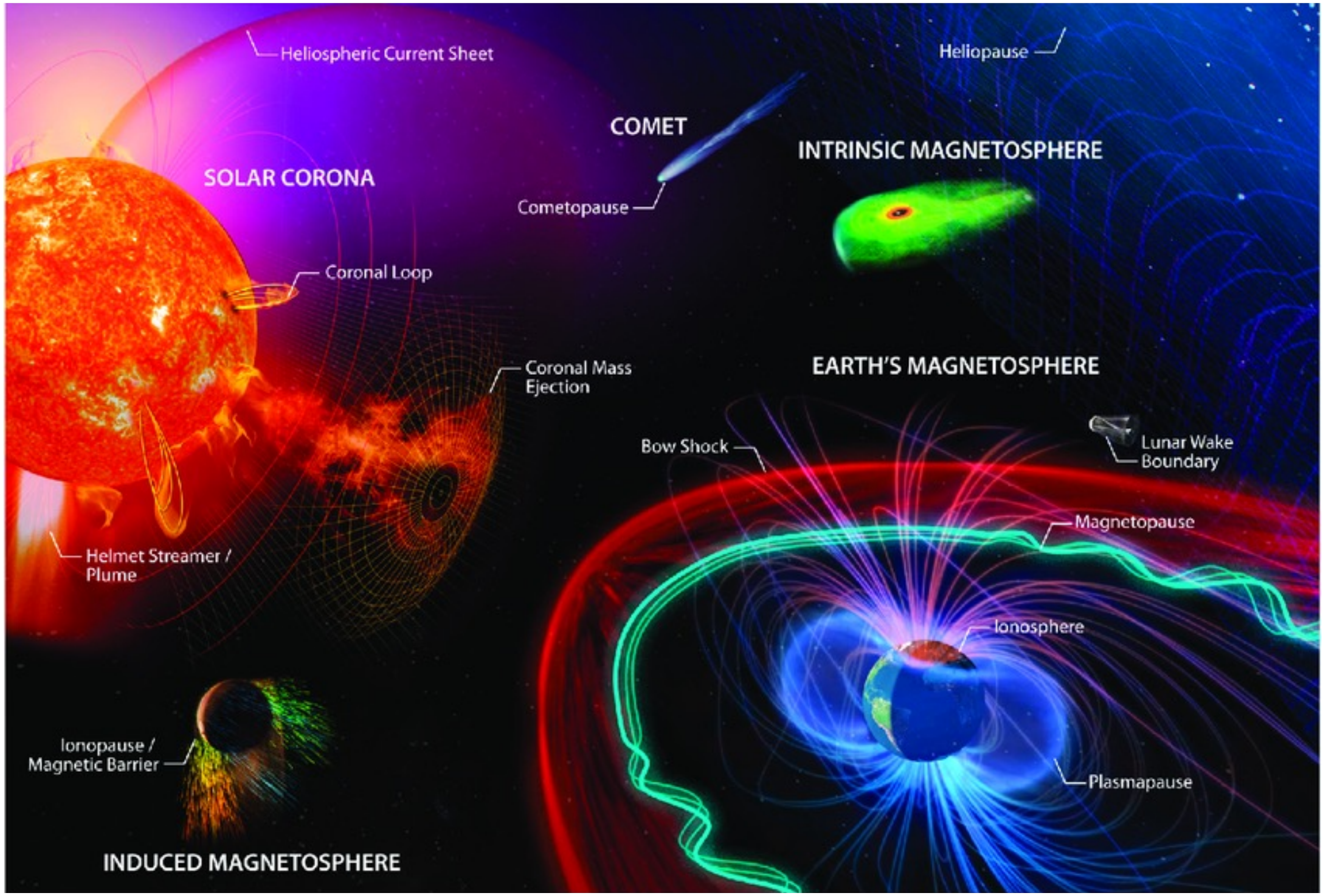
Low Energies: The Heliosphere



Low Energies: The Heliosphere

- Main plasma structures:
  - Solar corona (loops, holes, …)
  - Solar wind
  - Planetary magnetospheres

- Main plasma phenomena:
  - Coronal mass ejections
  - Solar-wind expansion
  - Solar-wind turbulence

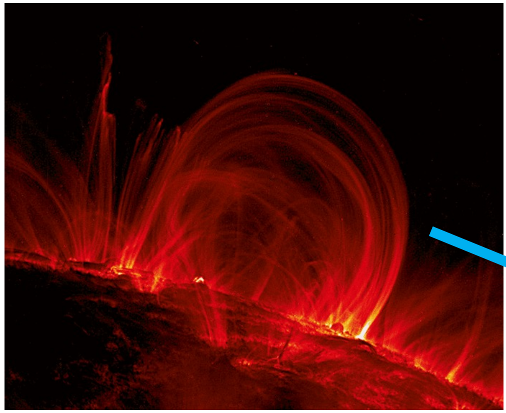


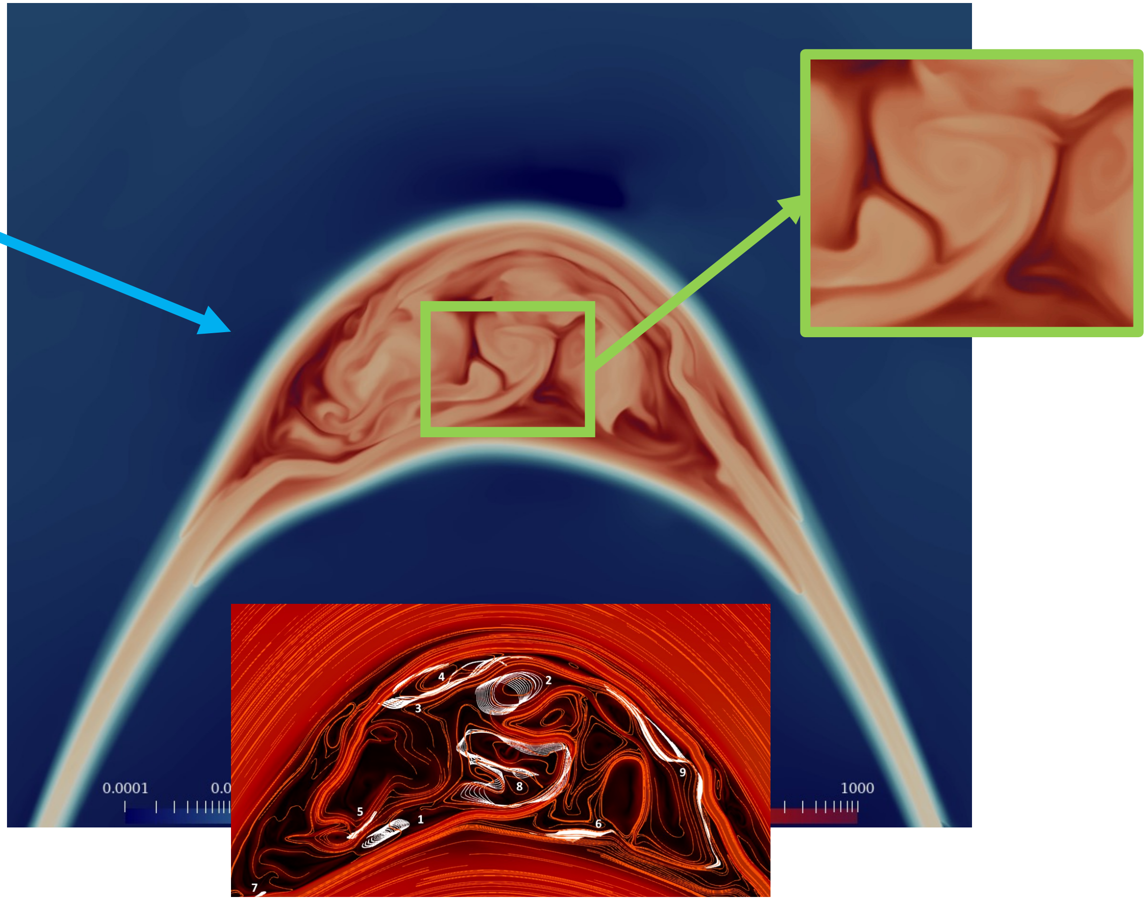
Low Energies, Large Scales: Coronal Loops

MACRO

MESO

MICRO





- Exploit AMR + particles
- Efficient parallelization
- Typical run ~1M CPUh

Bacchini+2024, Mora+2025

FLUID

HYBRID

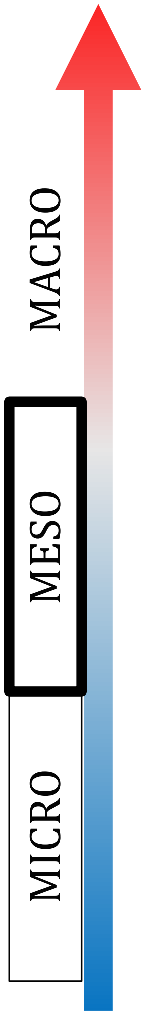
KINETIC

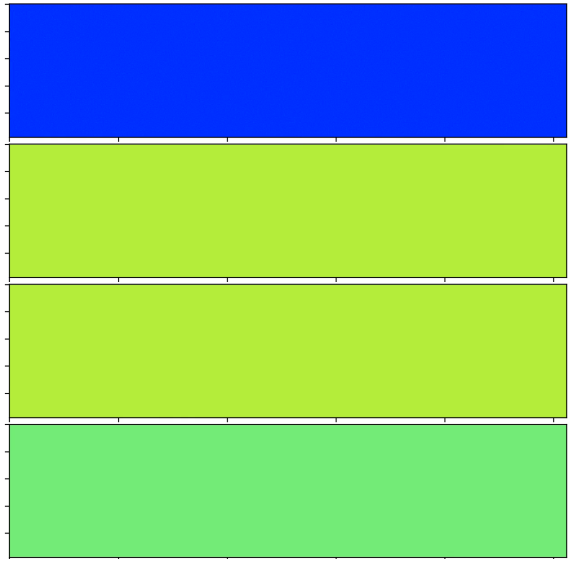
NEWTONIAN

TRANSRELATIVISTIC

RELATIVISTIC

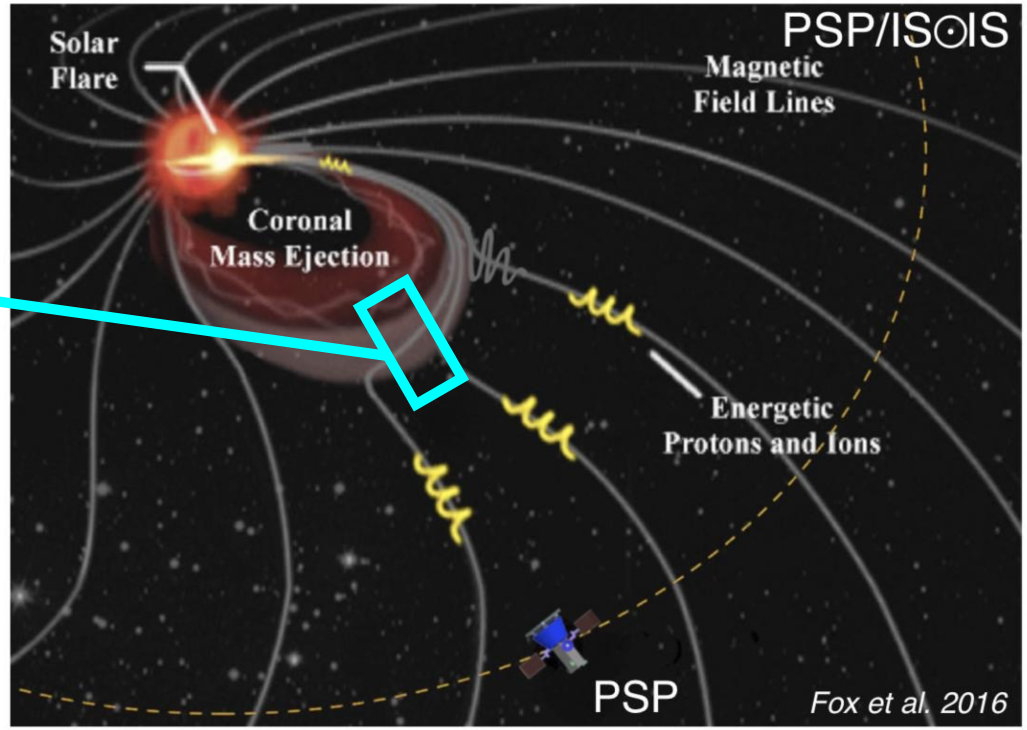
Low Energies, Large Scales: CME Shocks

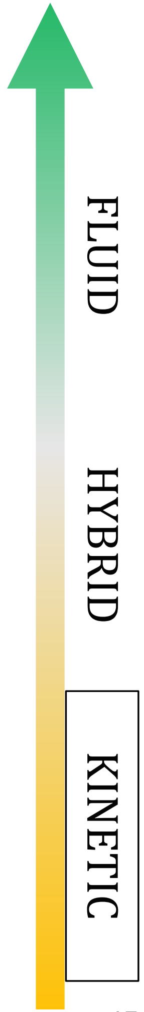




- Full-particle simulation
- Typical run ~5M CPUh
- Difficult parallelization

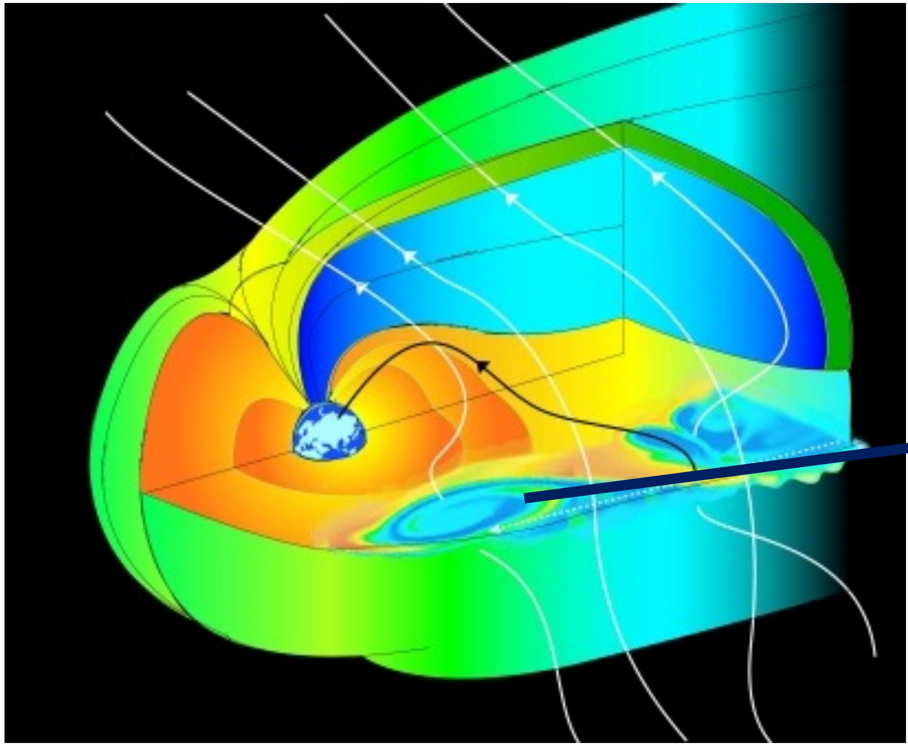
Wijsen&Bacchini in prep.





Low Energies, Large Scales: Earth's Magnetosphere

MACRO
MESO
MICRO



- Full-particle simulation
- Typical run ~2-5M CPUh
- Very long physical times
  → need better methods

Ferro+ in prep.

FLUID
HYBRID
KINETIC

NEWTONIAN TRANSRELATIVISTIC RELATIVISTIC

Low Energies, Small Scales: Solar-wind Expansion

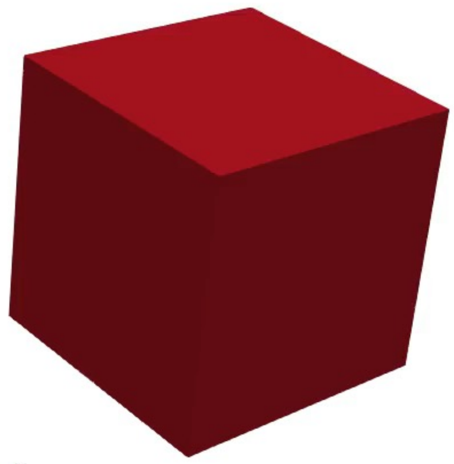
- Full-particle simulation
- Typical run ~10M CPUh!
- Very long times and large scales

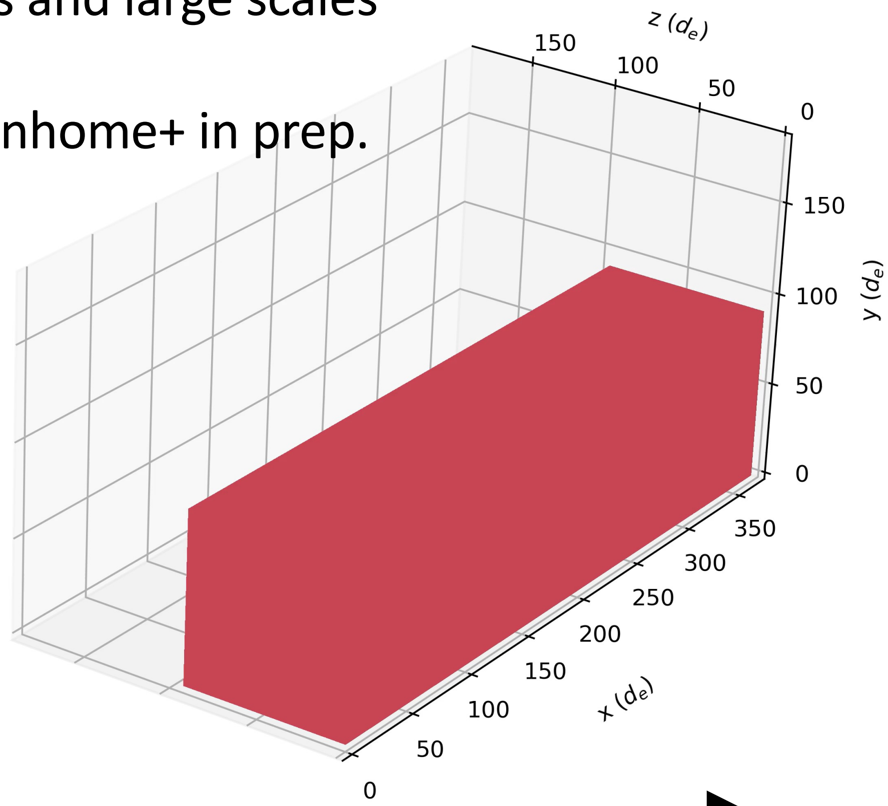
Peters de Bonhome+ in prep.

MACRO

MESO

MICRO





FLUID

HYBRID

KINETIC

NEWTONIAN

TRANSRELATIVISTIC

RELATIVISTIC

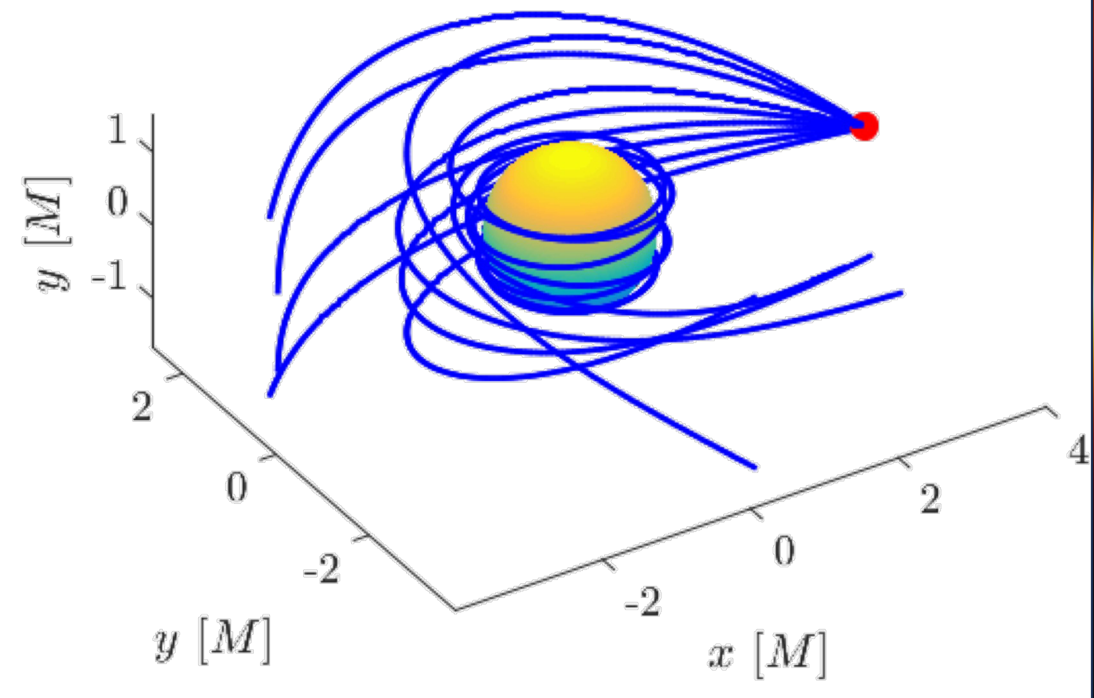
High Energies: Compact-object Environments

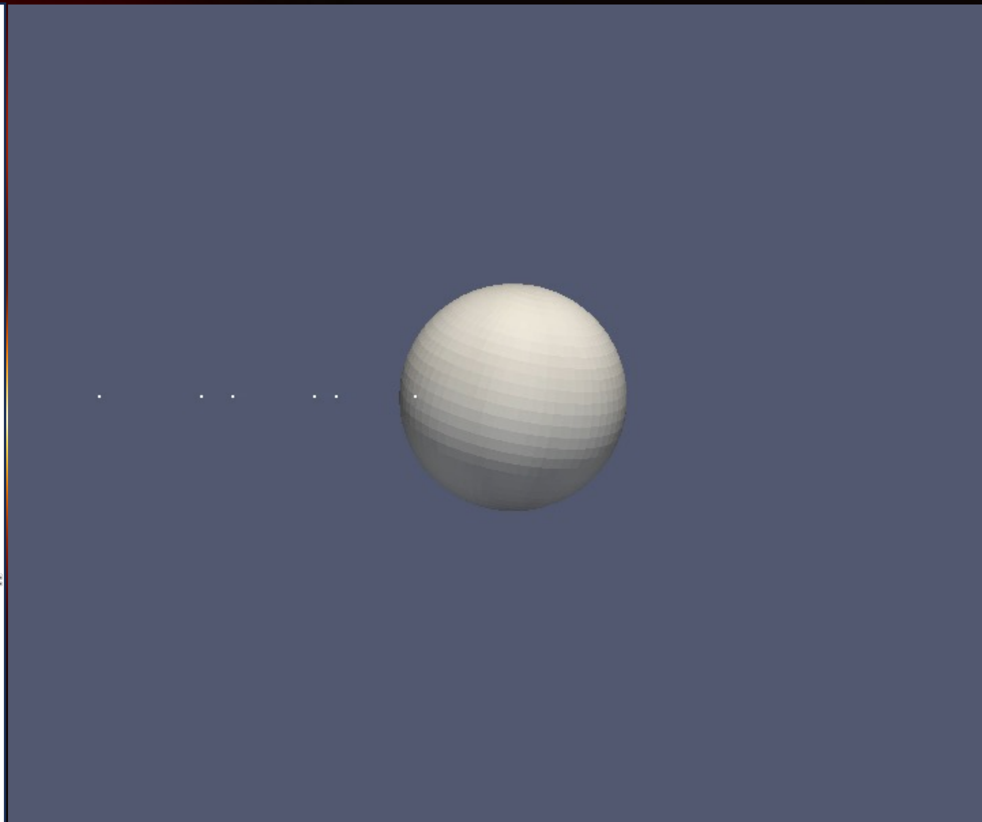
[EHT / Hotaka Shiokawa]

[EHT/BHC J. Davelaar]

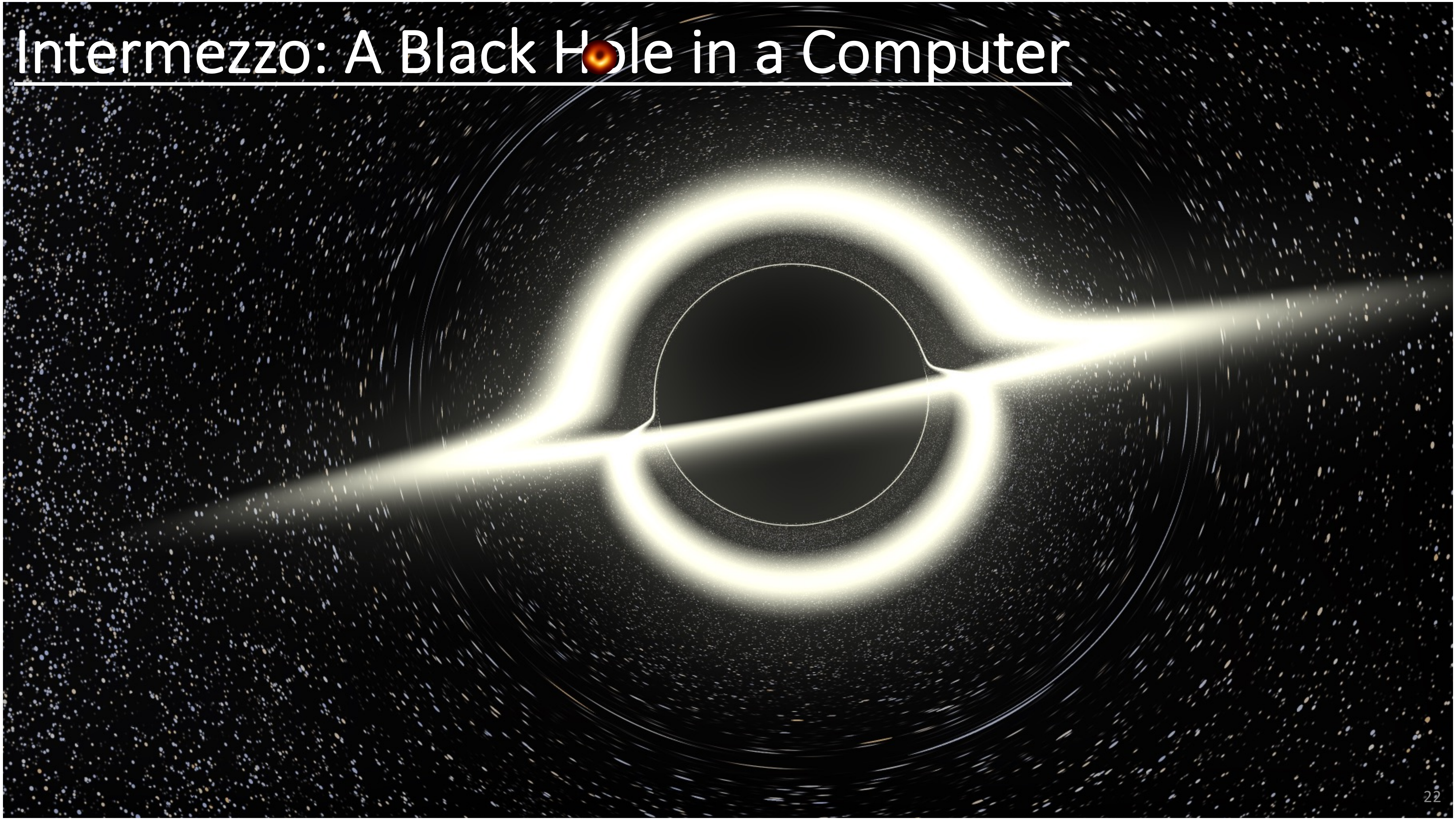
Intermezzo: A Black Hole in a Computer

$$\frac{\mathrm{d}u_\mu}{\mathrm{d}\tau} = -\Gamma^{\beta}_{\mu\alpha} u_\beta u^\alpha$$

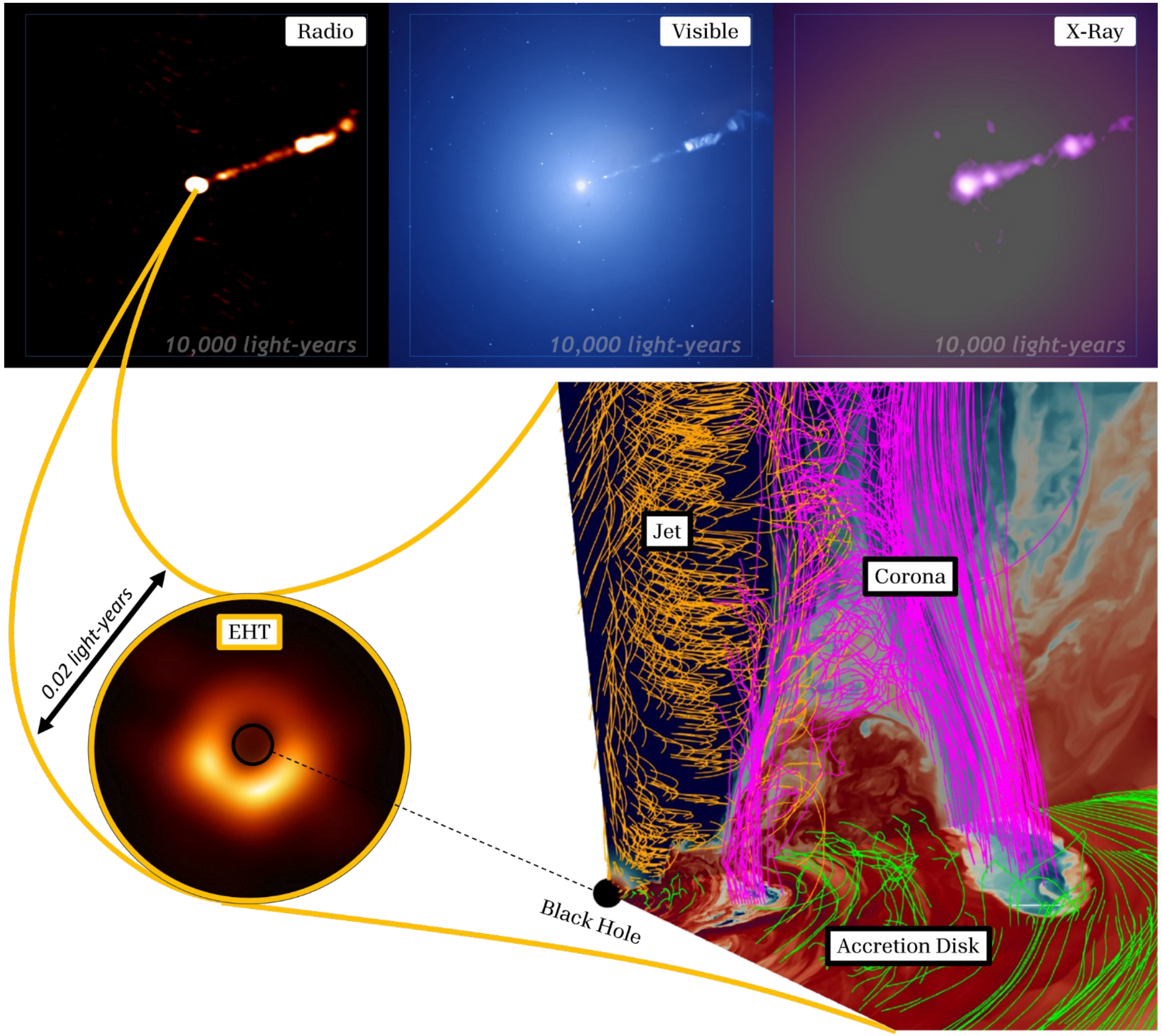


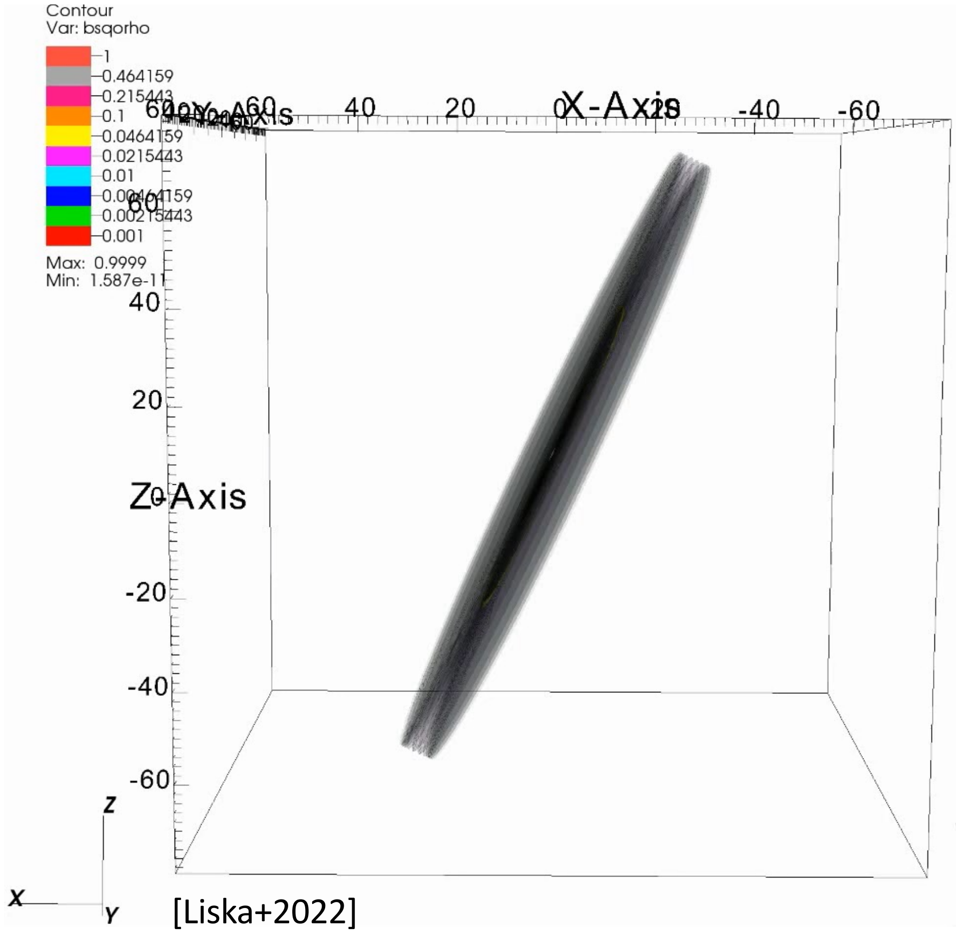


Intermezzo: A Black Hole in a Computer



Intermezzo: A Black Hole in a Computer





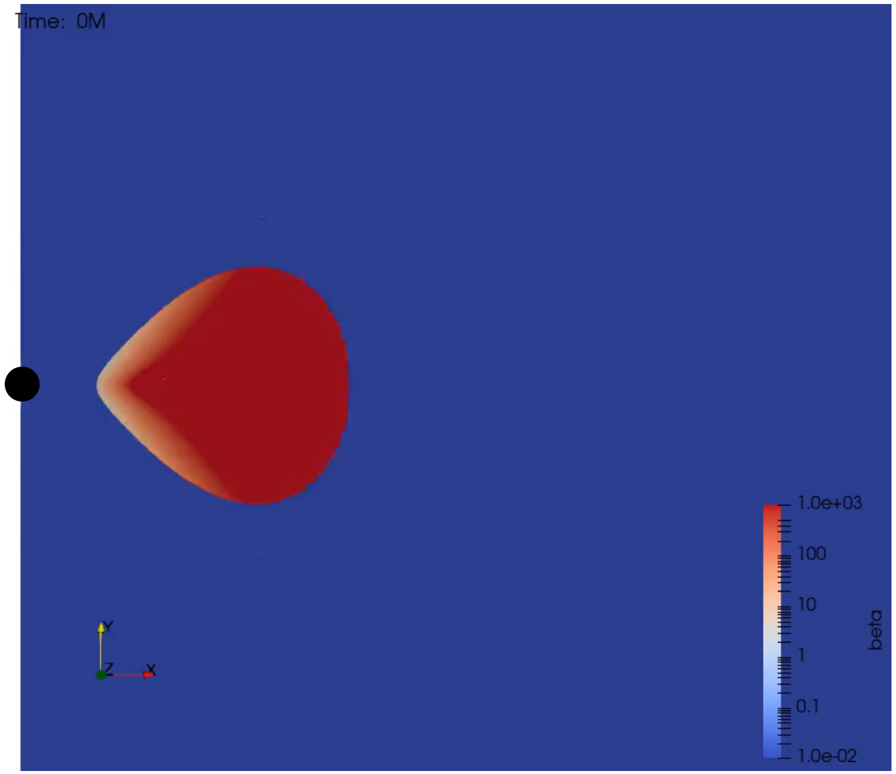
[Liska+2022]

High Energies, Large Scales: BH/NS Magnetospheres

MACRO

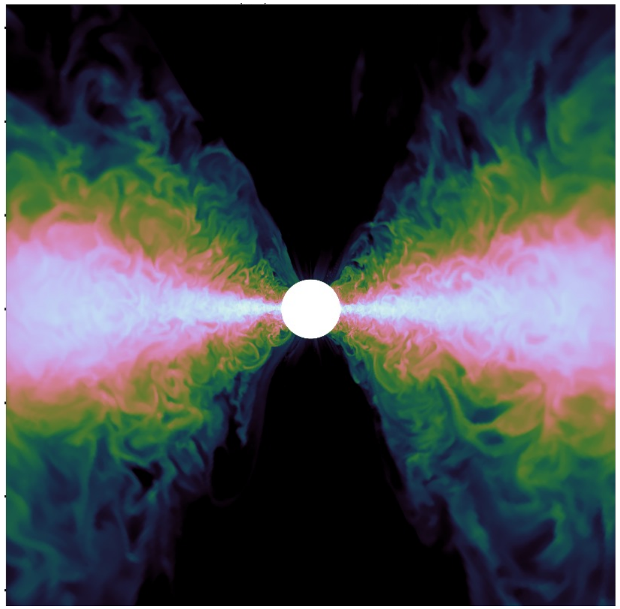
MESO

MICRO



- Fluid simulations (mostly)
- Typical run ~30k GPUh
- Very large scales, very long times

Ripperda&Bacchini+2019, Ripperda+2020



FLUID

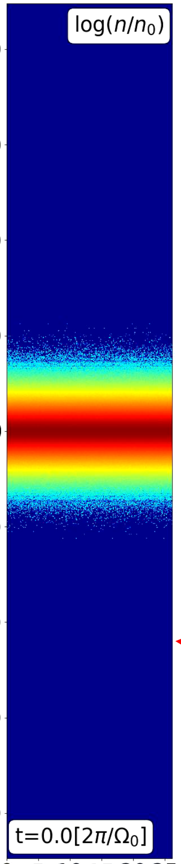
HYBRID

KINETIC

NEWTONIAN TRANSRELATIVISTIC RELATIVISTIC

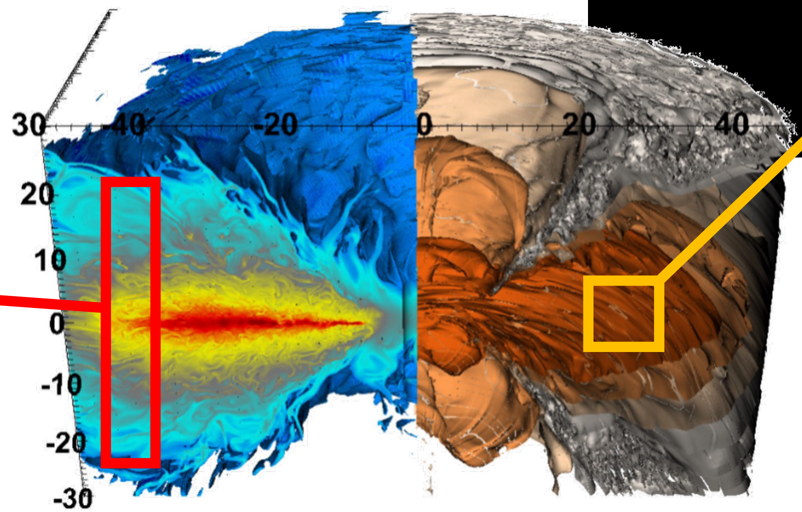
High Energies, Small Scales: Collisionless Accretion

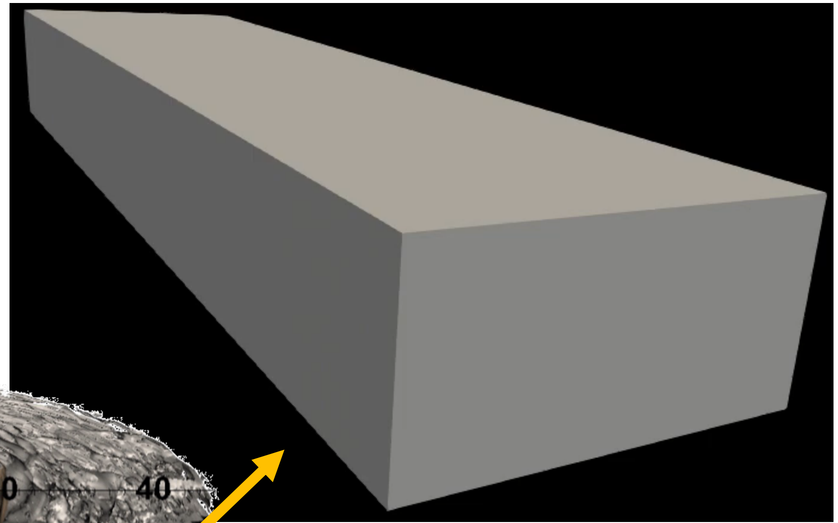
MACRO
MESO
MICRO



- Full-particle simulation
- Typical run ~20M CPUh!
- Very large scales, multiple species

Bacchini+2022,2024, Sandoval+2024, Gorbunov+2025





[Jiang+2014]

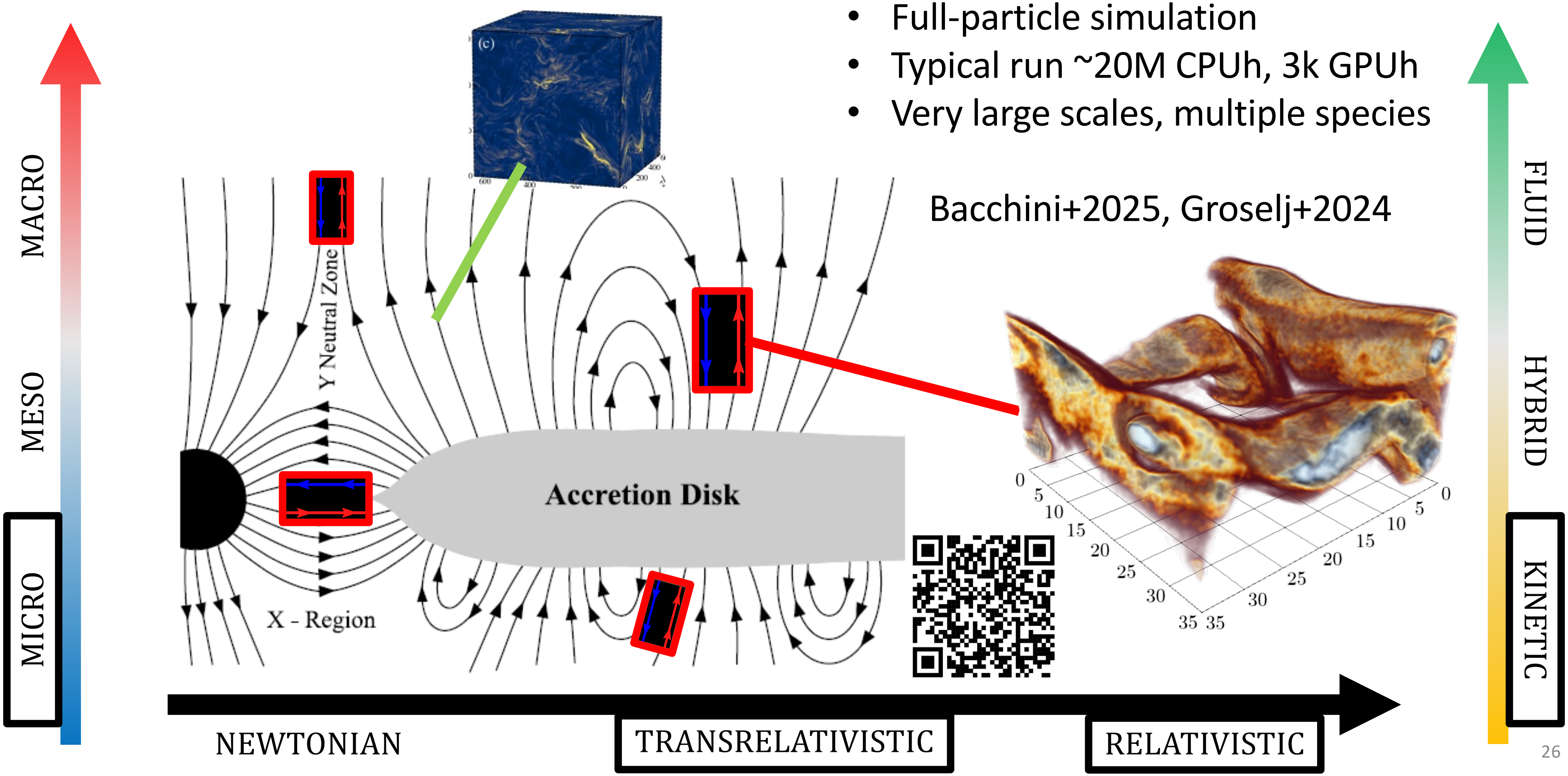
FLUID
HYBRID
KINETIC

NEWTONIAN
TRANSRELATIVISTIC
RELATIVISTIC

High Energies, Small Scales: BH Accelerators

- Full-particle simulation
- Typical run ~20M CPUh, 3k GPUh
- Very large scales, multiple species

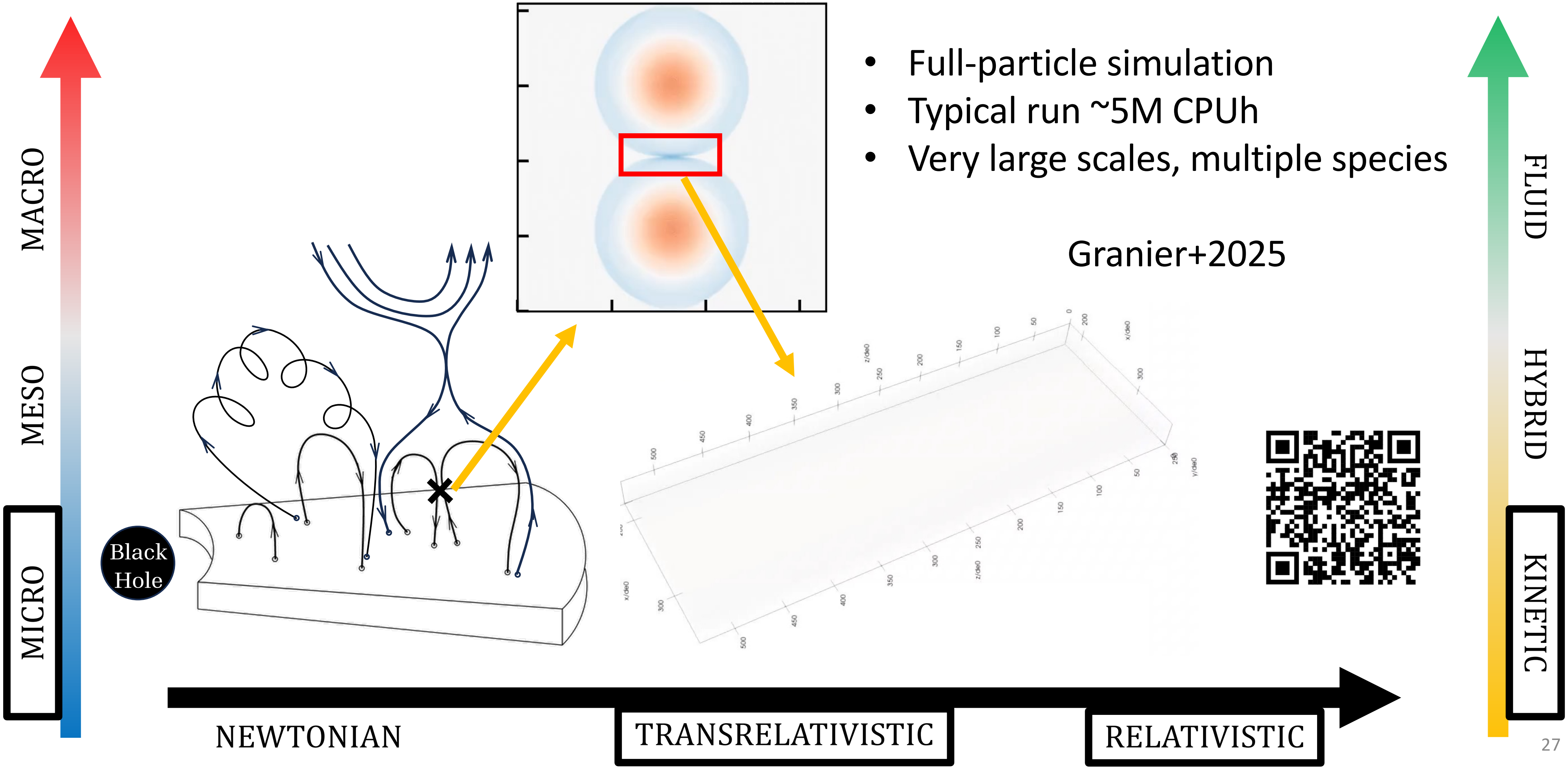
Bacchini+2025, Groselj+2024



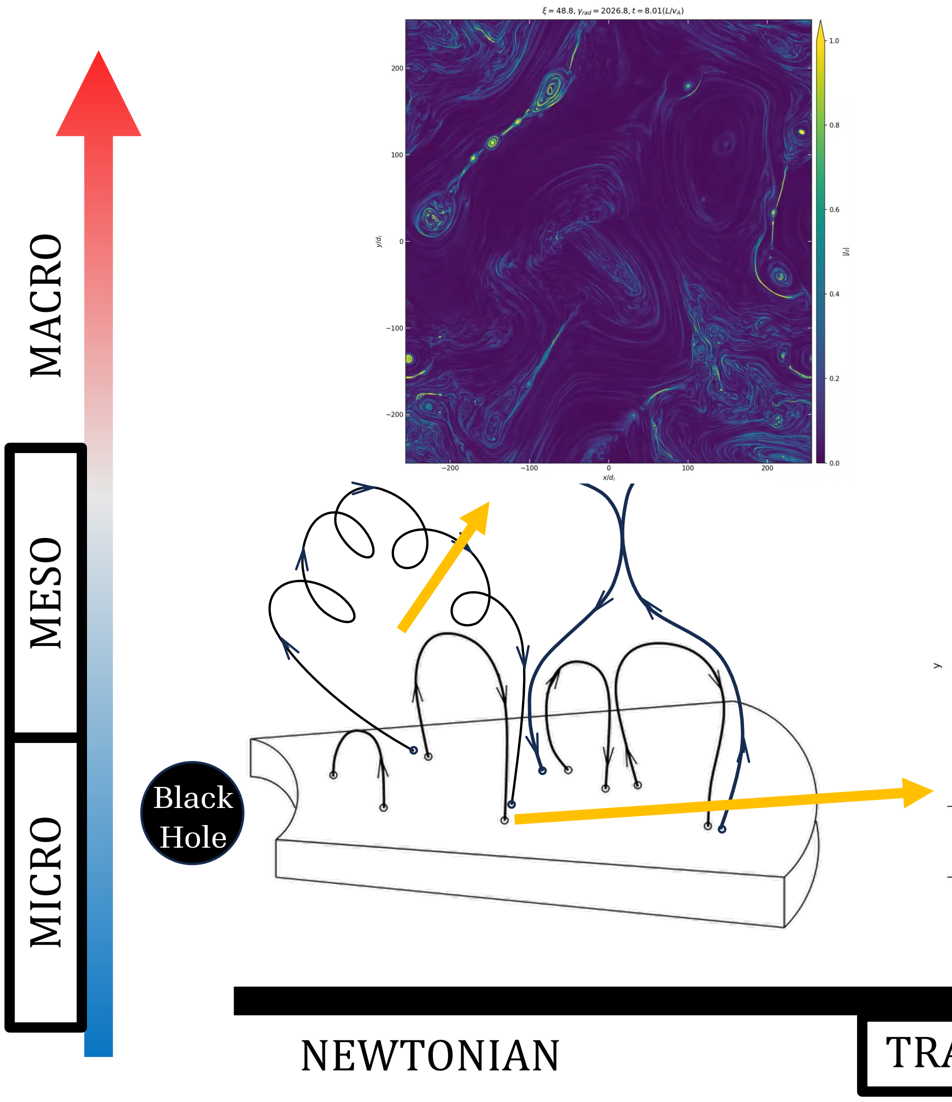
High Energies, Small Scales: BH Accelerators

- Full-particle simulation
- Typical run ~5M CPUh
- Very large scales, multiple species

Granier+2025

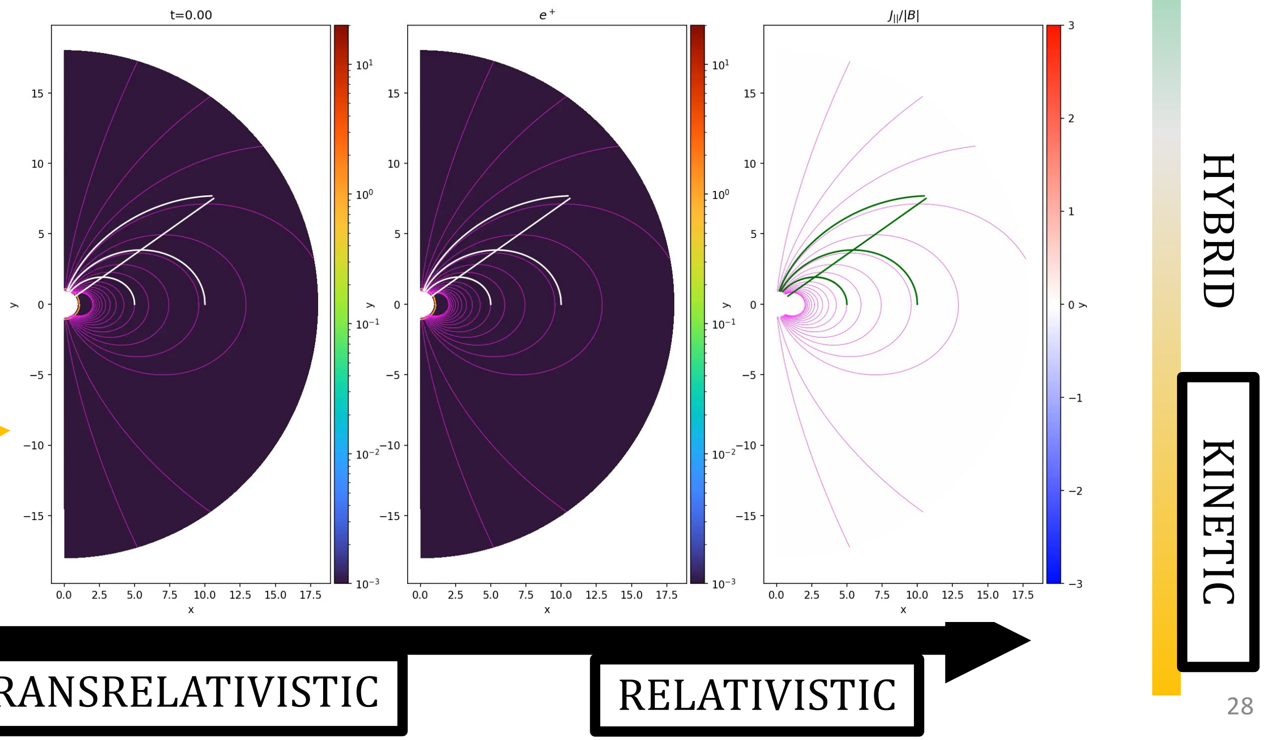


High Energies, Small Scales: BH Accelerators



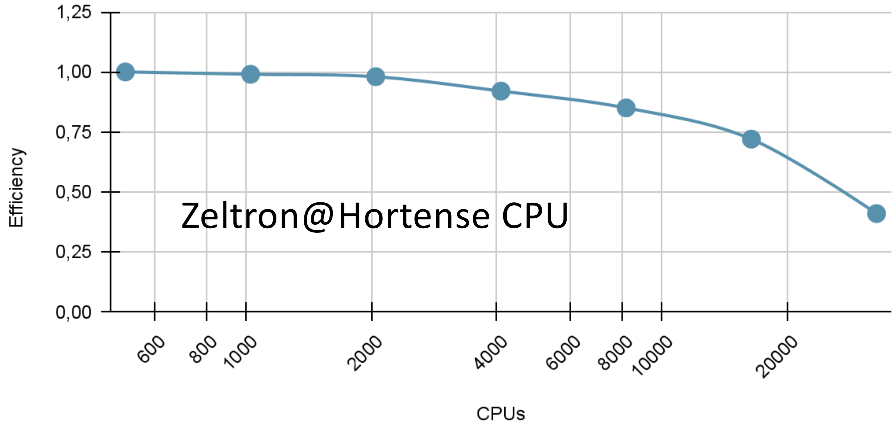
- Full-particle simulation
- Typical run ~3k-30k GPUh
- Power of GPUs!

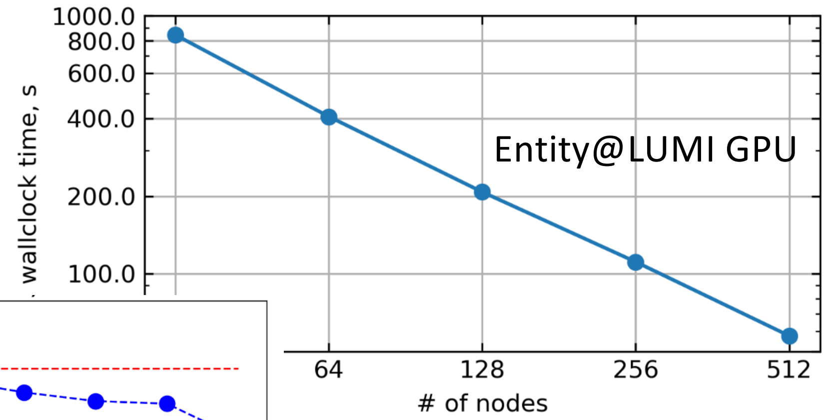
Chernoglazov+ in prep.

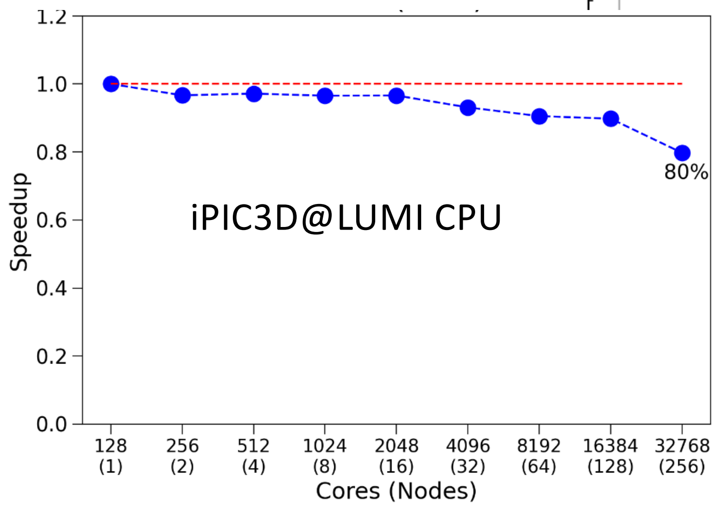


Actual HPC Stuff

- We have 6+ actively developed codes deployed on VSC/CSC infrastructures
- Most codes CPU based, recently 2 high-performance GPU codes
- Moving to GPUs not always entirely possible
- Active development projects include EuroHPC-SPACE EU-funded CoE

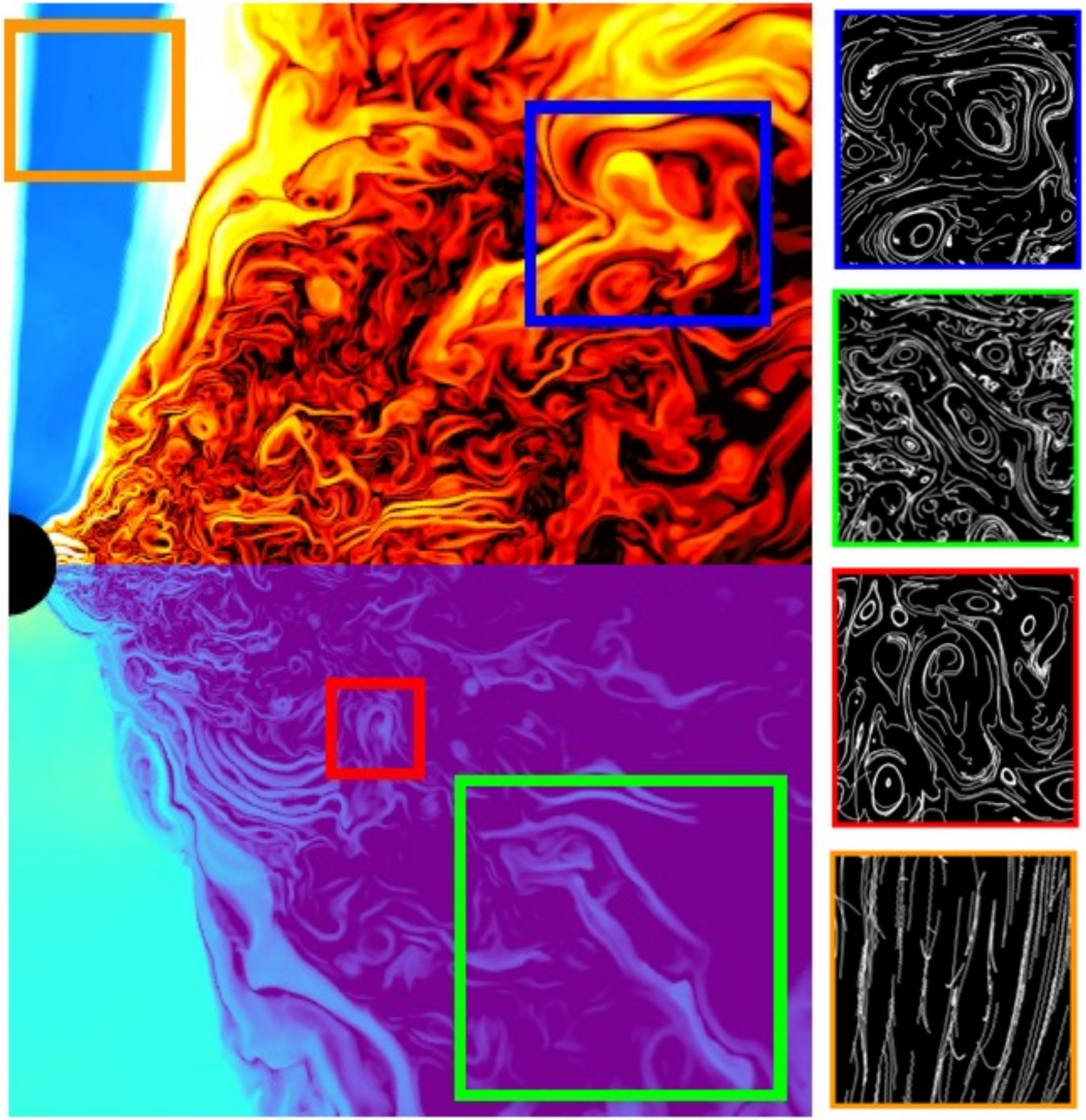






Summary

- Plasmas are cool! And they are everywhere
- HPC-powered full-particle models allow us to study plasmas at different time, length, and energy scales
- Basic plasma processes ubiquitous in the Universe → We can interpret observations!
- Ultimate goals:
  - Uncover unknown processes giving rise to radiation
  - Explore theories of gravity beyond GR
  - Protect ourselves from solar activity
  - Fun!



fuse*: Sál

[Sál – fuse*]